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Effect of Micro Injection Molding Parameters on Cavity Pressure and Temperature Assisted by Taguchi Method

Quan WANG*, Chongying YANG, Kaihui DU***, Zhenghuan WU******
**National Local Joint Engineering Laboratory of Intelligent Manufacturing Oriented Automobile Die& Mold, Tianjin University of Technology and Education, Tianjin, 300222, China, E-mail: wq2001126@163.com*
***College of mechanical engineering, Tianjin University of Technology and Education, Tianjin, 300222, China, E-mail: yangcy521@163.com*
****College of mechanical engineering, Tianjin University of Technology and Education, Tianjin, 300222, China, E-mail: 360066439@qq.com*
*****College of mechanical engineering, Tianjin University of Technology and Education, Tianjin, 300222, China, E-mail: wzh46817@163.com*

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1. Introduction

Injection molding technology has been used for more than 100 years. However, the production of micro- and Nano-parts by this method is still new [1, 2]. Current research is focused on applying this technology to the fabrication of small, affordable parts, instead of using expensive conventional techniques. Micro- and Nano-scale injection moldings of small complex parts are mainly used in electronic and micro-electromechanical systems and biological applications [3, 4]. Micro-injection molding is utilized with micro-weights parts; that is, the weight of the parts is on the order of a few milligrams, but the dimensions are not on a micron scale. This technique also involves parts with micro-structured regions (e.g., micro-slots, micro-holes) and parts with micro-precision dimensions. Thus, such products require a micron-range tolerance [5].

Increased demand for micro-scale parts and devices are being met in many cases by micro-injection molding of polymer parts. However, part inspection is difficult due to the micro-scale dimension in the micro-injection molding process. In addition, process control also becomes challenging since the process is susceptible to slight changes in process parameters such as mold temperature, injection velocity, and packing pressure etc. [6-8]. To address these issues, a suitable process monitoring method such as cavity pressure monitoring can be employed to detect any process deviation that may cause defects in part quality. Cavity pressure has been found to be a reliable process indicator in injection molding for both part quality and process monitoring. Specifically, it has been found to provide real-time detection of part and process deviation [9-13]. As such, cavity pressure measurement holds potential for monitoring part quality in micro-injection molding where direct part inspection is difficult and often costly due to part handling issues and microscopic feature sizes.

Although the processing window for micro-injection molding was smaller than macro-molding, the cavity pressure and temperature curves were able to capture the differences in molding conditions. Furthermore, attributes obtained from the pressure curve such as peak cavity pressure was found to have good correlation with part weight which was used as the quality metric [14]. In terms of defects among the parts, peak cavity pressure was able to detect defective parts based on the measured peak cavity pressure value. The finding from the current investigation demonstrates significant potential for cavity pressure to be utilized as an indicator of part quality as well as a process monitoring tool for the microinjection molding process [15-19]. Moreover, effect of injection molding parameters of injection molded polymer materials on the cavity pressure is less been reported.

In order to investigate the mechanism of micro injection molding parameters on cavity pressure and temperature, the diverse spline was conducted using polypropylene under varying processing parameters to observe how cavity pressure and temperature responded to the different molding conditions in this paper. The final part of the investigation involved using the orthogonal design approach to include a broader range of processing parameters.

2. Taguchi design

In the process of injection molding, parameters in injection process can significantly influence the quality of injection-molded parts. Therefore in actual productions, a number of test factors need to be investigated simultaneously. However, overall test is difficult to be carried out due to large test scales and limits of test costs. Orthogonal design is a high-efficiency design method for tests to arrange multi-factor tests and seek optimal level combinations. The design method of orthogonal tests is able to determine optimal parameters by simply calculating influences of each factor on test results, showing the influences in charts, and then comprehensively comparing differences. The calculation is carried out on orthogonal tables, so the whole process is simple and clear. In this way, enough information can be obtained through a few tests, thus saving costs. The parameters used for the cavity pressure and temperature were the melt temperature (A), mold temperature (B), packing pressure (C), packing time (D) and injection pressure (E). The values of these parameters are presented in Table 1.

2.1. Taguchi design of tensile specimen

An $L_{16}(4^5)$ orthogonal array was selected for the experimental design for each of the five factors. The four levels for the five parameters were identified during the 16 experiments. The values of these parameters are presented in Table 2**.** The experiments were carried on micro injection molding machine. The real-time curves of data were output, and the average value of maximum tensile spline of cavity pressure were obtained.

Table 1

Process parameters and their levels

Factor	*A*	*B*	*C*	*D*	*E*
	Melt temperature, ℃	Mold temperature, ℃	Packing pressure, MPa	Packing time, s	Injection pressure, MPa
1	220	40	85	5	85
2	230	50	90	10	90
3	240	60	95	15	95
4	250	70	100	20	100

Table 2

Proposed $L_{16}(4^5)$ orthogonal array of tensile specimen

Run	*A*, ℃	*B*, ℃	*C*, MPa	*D*, s	*E*, MPa	Max average value/bar
1	220	40	85	5	85	395.08
2	220	50	90	10	90	473.91
3	220	60	95	15	95	524.11
4	220	70	100	20	100	591.79
5	230	40	90	15	100	486.71
6	230	50	85	20	95	454.38
7	230	60	100	5	90	604.60
8	230	70	95	10	85	608.54
9	240	40	95	20	90	543.94
10	240	50	100	15	85	628.34
11	240	60	85	10	100	498.69
12	240	70	90	5	95	556.84
13	250	40	100	10	95	626.20
14	250	50	95	5	100	609.91
15	250	60	90	20	85	541.86
16	250	70	85	15	90	523.21
K_1	496.222	512.983	467.840	541.607	543.455	
K_2	538.558	541.635	514.830	551.835	536.415	
K_3	556.953	542.315	571.625	540.592	540.382	
K_4	575.295	570.095	612.733	532.993	546.775	
R	79.073	57.112	144.893	18.842	10.360	

K_1 ,K_2 ,K_3 ,K_4 is variance，*R* is range

Based on the experimental results of Table 2, the range *R* value is greater and the impact of the factors is greater on the test index. For the tensile spline, the order of the injection molding process parameters on the maximum value of the cavity pressure is: *C* (packing pressure) >*A* (melt temperature) >*B* (mold temperature) >*D* (packing time) >*E* (injection pressure).

To further analyse the variance of the results, the influence of the process parameters on the maximum value of mold cavity pressure can be analysed. It can be seen from the Table 3, the influence of packing pressure on the mold cavity pressure is larger. According to F value, the pressure of the mold cavity pressure has significant influence on the cavity pressure. The melt temperature, mold temperature, packing pressure time and injection pressure to the mold cavity pressure maximum influence is smaller.

Table 3

Variance analysis of tensile specimen

Factor	Square of deviance	DoF	Variance	Average variance	Significant
A	13757.313	3	4585.771	0.987	
B	6524.361	3	2174.787	0.468	
C	48473.621	3	16157.874	3.477	*
D	719.044	3	239.681	0.052	
E	233.959	3	77.986	0.017	

2.2. Taguchi design of impact specimen

The average value of the pressure of the impact sample is shown in Table 4. According to the analysis of the experimental results in Table 4, can be seen for the impact spline, the effect order of injection molding process parameters on the maximum cavity pressure is as follows: *C* (packing pressure) >*A* (melt temperature) >*B* (mold temperature) >*D* (packing time) >*E* (injection pressure).

Table 4

Proposed $L_{16}\,(4^5)$ orthogonal array of impact specimen

Run	*A*	*B*	*C*	*D*	*E*	Max average value/bar
1	220	40	85	5	85	421.71
2	220	50	90	10	90	501.08
3	220	60	95	15	95	552.35
4	220	70	100	20	100	621.90
5	230	40	90	15	100	511.75
6	230	50	85	20	95	476.90
7	230	60	100	5	90	635.52
8	230	70	95	10	85	640.76
9	240	40	95	20	90	571.25
10	240	50	100	15	85	662.17
11	240	60	85	10	100	523.71
12	240	70	90	5	95	585.18
13	250	40	100	10	95	659.74
14	250	50	95	5	100	642.40
15	250	60	90	20	85	572.51
16	250	70	85	15	90	548.88
K_1	524.260	541.112	492.800	571.202	574.287	
K_2	566.233	570.638	542.630	581.322	564.183	
K_3	585.577	571.023	601.690	568.788	568.543	
K_4	605.883	599.180	644.832	560.640	574.940	
R	81.621	58.068	152.032	20.682	10.757	

Further variance analysis was carried out on the above results, and the influence of process parameters on the maximum value of mold cavity pressure was analysed. As can be seen from the Table 5, the factor *C* (packing pressure) is 3.516, which shows that the influence of packing pressure of the mold cavity pressure is significant.

Table 5

Variance analysis of impact specimen

Factor	Square of deviance	DoF	Variance	Average variance	Significant
A	14542.404	3	4847.468	0.960	
B	6745.836	3	2248.612	0.445	
C	53248.652	3	17749.551	3.516	*
D	871.087	3	290.362	0.058	
E	311.203	3	103.734	0.021	

3. Experimental

Materials: The sample material used in this work was polypropylene in the form of pellets and with a trade mark 5090T (MFI=15g/10min), supplied by the Formosa petrochemical Corp, Taiwan.

Mold: The multi-spline injection mold constructed from two parts (tensile specimen and impact specimen) shown in Fig. 1. The mold cavity of thicknesses is 1 mm. Fig. 2 shows the product produced by the injection molding and the cavity pressure is measured at the back of the part.

Injection molding machine: The experimental work was carried out on an injection molding machine of type BOX XS concept having a maximum injection pressure 2298 bar, with screw diameter for plastication 14 mm and maximum weight of the product 6.1 g.

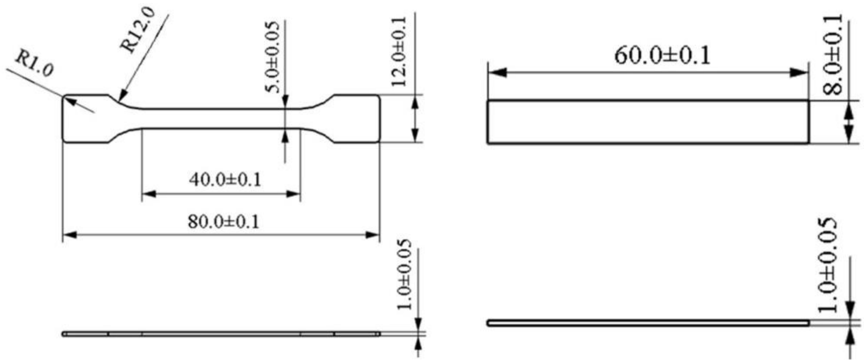


Fig. 1 Geometry and dimensions of the tensile and impact specimen

Amplifier (type Kistler 1708B0): It is used to convert the electrical charge of the pressure sensor signals yielded by piezoelectric into proportional voltages. The output of the amplifier is transferred to the center of acquisition system and another output is transferred to a universal indicator. The output signals from the amplifier are 0–10 DC voltages which are transmitted to the recorder and the data acquisition system.

Acquisition data: Data output from the amplifier is collected using a Kistler 5865 Como injection system. Computer is used to record the output reading of the acquisition system through an interface cart by the help of lab view program.

Kistler 6190CA: The cavity pressure and temperature is measured in the mold cavity by the quartz sensor for mold cavity pressure type Kistler 6190CA, which has a front of 4.0 mm diameter. The pressure transducer has a sensibility of 2.5 bar and it is able to register changes of the pressure as a function of time with the resolution up to 0.01 s. The pressure acting directly on the entire front of the sensor is transferred to the quartz measuring element, which produces an electrical charge proportional to the pressure.

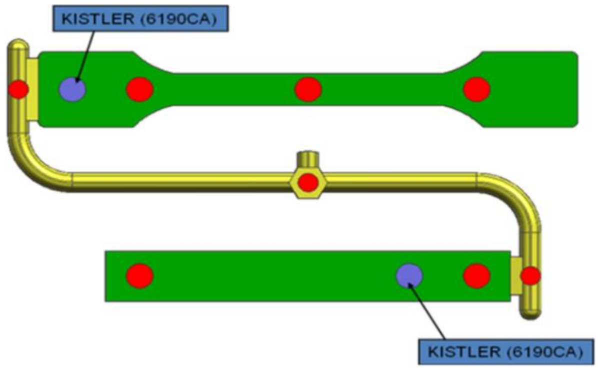


Fig. 2 Locations of sensors in the mold

Mold temperature controller：The mold temperature controller (model TP6ZE) was adopted using PIOVAN Co. Ltd, Italia.

Chiller：Chiller (model ML-CA03) was adopted using Ming Lee Co. Ltd, Hong kong , China.

The experimental equipment of micro injection molding for measuring cavity pressure and temperature is shown in Fig. 3.

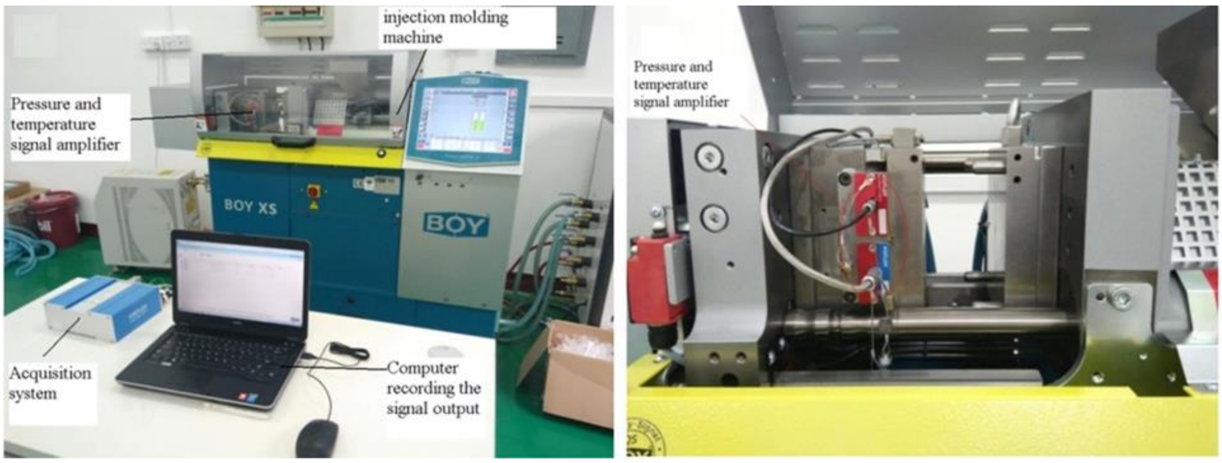


Fig. 3 Experimental equipment of injection molding

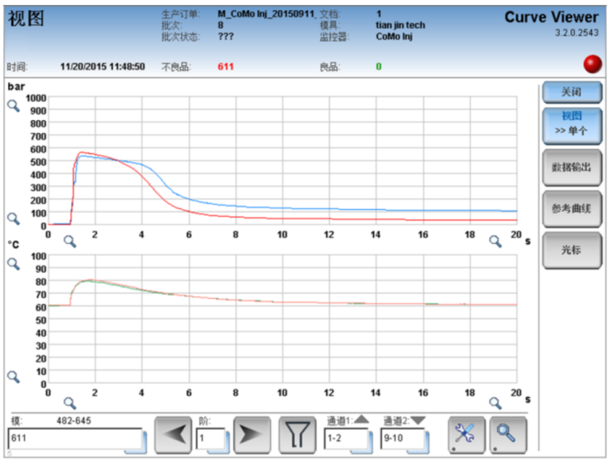


Fig. 4 Real-time data acquisition

The polymer material inside the hopper passes to the plasticization cylinder where it is melted to the injection temperature and injected to the mold cavity through the runner and gate. The hot plastic material injected inside the cavity is cooled by cooling water circulating through four cooling channels inside the fixed and movable parts. At the end of the cooling stage, the product is ejected out of the machine to start a new cycle. The real-time data acquisition of cavity pressure and temperature are shown is Fig. 4. During the experimental work and for each case studied, the following procedures are performed:

1. Adjust the cooling water inlet to have the same inlet temperature and flow rate for all cases.

2. Adjust the process parameters (melt temperature, packing time, injection pressure, etc.) of the injection molding machine by the machine regulator to suit each studied case and wait until reaching steady-state values especially for inlet polymer temperature before starting the injection molding cycle.

3. Wait sufficient time until all the thermocouple readings by the recorder have the same values to ensure that the mold temperature is initially at the same temperature of water inlet.

4. Run the acquisition data system for reading all of the input values (mold temperature, inlet temperature of cooling water flow rate, and cavity pressure).

5. Run the lab view program through the computer to record the output data from the acquisition data system in a separate file inside the computer.

6. Run the injection molding machine to start mold cycles until finishing the required cycles for each case studied.

7. During all case studied, verifying that the values of the flow rate and inlet water temperature are constant during each experimental case by verifying their value through the indicator.

8. Wait until the reading of all thermocouple gives the same reading of the initial value of the inlet water temperature.

9. Repeating the same previous procedures to start another case.

4. Results and discussion

The parameters of injection molding process have different influences on the maximum cavity pressures and temperature of multi-spline samples. Fig. 5 show the curve relationship between melt temperature and the maximum cavity pressure and temperature in a double-cavity mold. In the Fig. 5, the maximum cavity pressure of tensile and impact pressures dramatically and then slowly increases with melt temperature. When the melt temperature is low, high filling cavity pressures and shear stresses in cavities result in the rapid increase of pressures. With the rise of temperature of plastic melts, the viscosity of polymer decreases continuously and the pouring gates coagulate slowly. In addition, it needs a long time to fill materials during which little pressure is lost, thereby increasing the maximum cavity pressure. With same injection processing parameters, the average value of the maximum cavity pressure of impact samples is larger than that of tensile samples. It is obvious that the pressures of cavities in the two types of samples are different in the injection. The injection processing parameters exert dissimilar effects on cavity temperature. With same injection processing parameters, the average value of the maximum cavity temperature of impact samples is higher than that of tensile samples. The maximum cavity temperature continuously increases with melt temperature. The direct-contact pressure-temperature sensor used in the test is directly contacted with plastic melts, the increase of melt temperature can affect the temperature measured by the sensor. Therefore, the maximum cavity temperature measured by the sensor rises correspondingly.

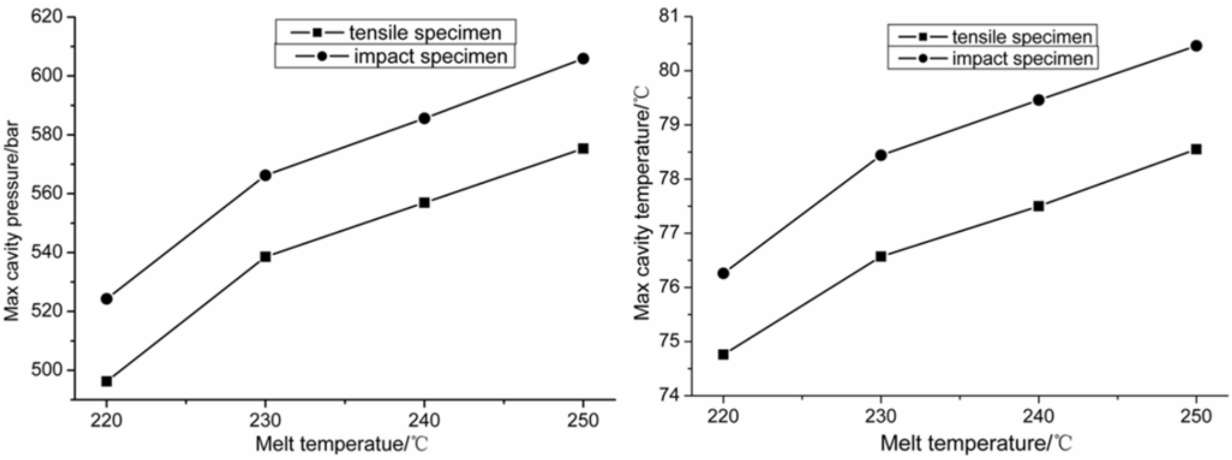


Fig. 5 Relationship between melt temperature and the maximum cavity pressure and temperature

Fig. 6 demonstrate the curve relationship between mold temperature and the maximum cavity pressure and temperature. It can be seen from the figure that the two curves increase first and stabilize, and then increase constantly. The higher the mold temperature, the more easily the melt enter into cavities of molds, thus improving the fluidity of melts in cavities and reducing pressure losses. In addition, in the stage of packing pressures, the increase of mold temperature makes it easy for melts to enter into cavities and decreases pressure losses. This is the reason why the maximum cavity pressure constantly increases with the rise of mold temperature. With the constant increase of mold temperature, the maximum cavity temperature rises correspondingly in an approximately linear manner with a small difference. Due to the efficiency of the mold temperature controller directly acts on mold cores, after setting values on the mold temperature controller, the efficiency is also directly reflected by cavity temperature measured by the sensor. In conclusion, mold temperature is a significant parameter for the maximum cavity temperature.

The curve relationship between packing pressures and the maximum cavity pressure and temperature is shown in Fig. 7. With the constant increase of packing pressures, the maximum cavity pressure also rises, almost showing linear relationship. If the packing pressure is low, it fails to overcome the resistances of pouring gates, resulting in low cavity pressures. So, increasing packing pressures can overcome the resistances of pouring gates and plastic melts can smoothly enter into cavities for feeding, thereby raising the maximum cavity pressure. Packing pressure significantly influences the maximum cavity pressure. The maximum cavity temperature of tensile samples slowly increases all the time, while that of impact samples slightly fluctuates in the beginning and then increases dramatically. The reason is that in the stage of packing pressures, if the packing pressures are small, plastic melts are hard to enter into cavities and cannot compensate temperature losses. If the packing pressures are too large, supplementary melts can enter into cavities, thus compensating temperature losses and raising the maximum cavity temperature.

The curve relationship between packing time and the maximum cavity pressure and temperature in a double-cavity mold is displayed in Fig. 8. The pressure curves of two cavities are similar. With prolonging packing time, the maximum cavity pressure increases firstly and then decrease after reaching to a certain value. If the packing time is too long, melts in cavities have been coagulated while pouring gates are not coagulated, so the maximum value of the whole cavity pressure reduces. The values of maximum cavity temperature of the two samples constantly decline with packing time. Because packing time is prolonged, plastic melts in cavities are coagulated, thereby reducing the temperature in cavities.

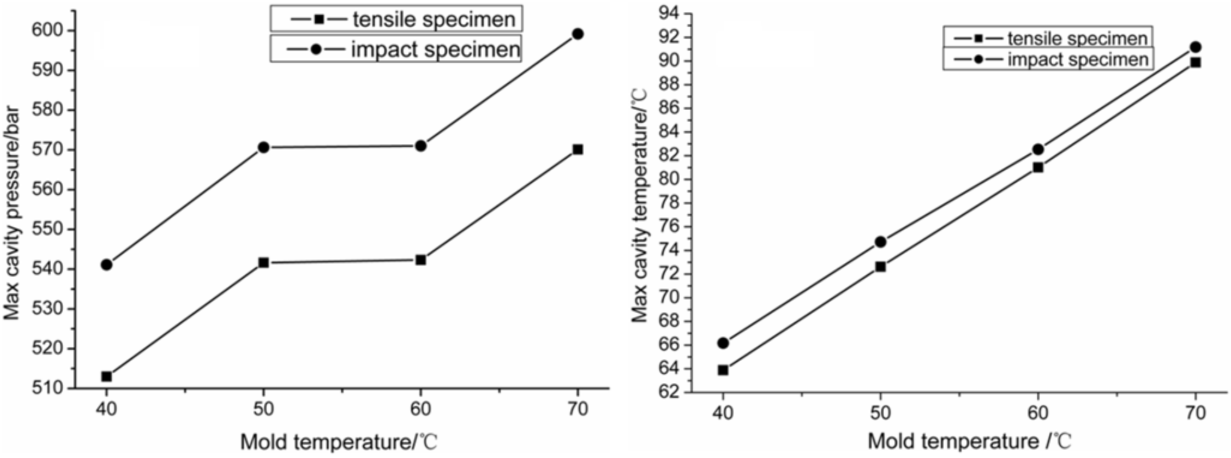


Fig. 6 Relationship between mold temperature and the maximum cavity pressure and temperature

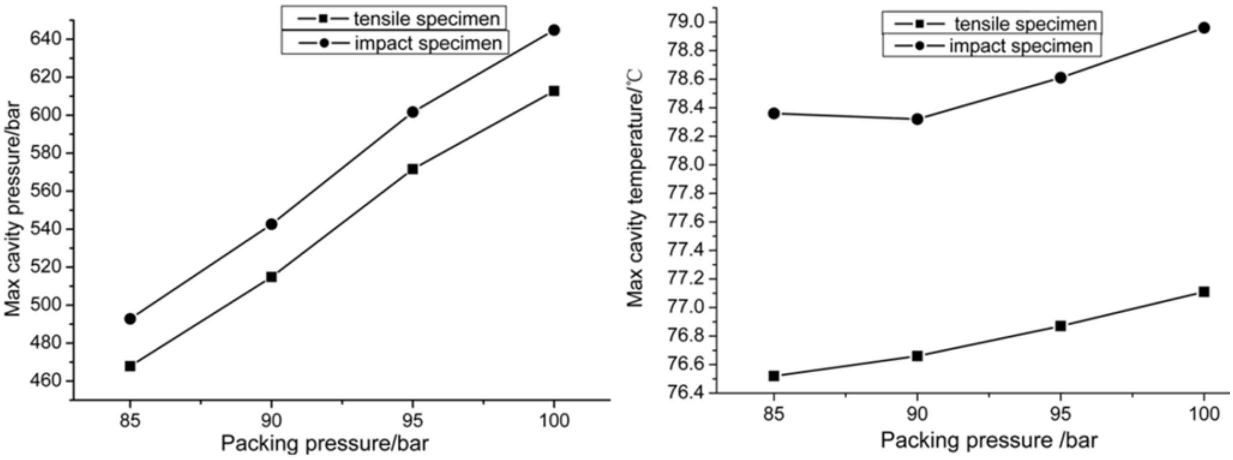


Fig. 7 Relationship between packing pressure and the maximum cavity pressure and temperature

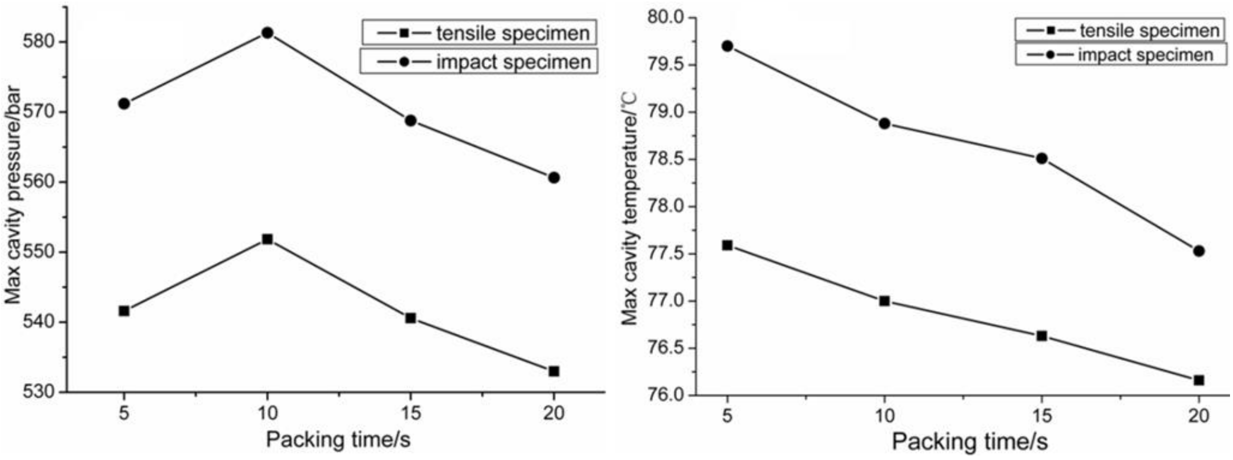
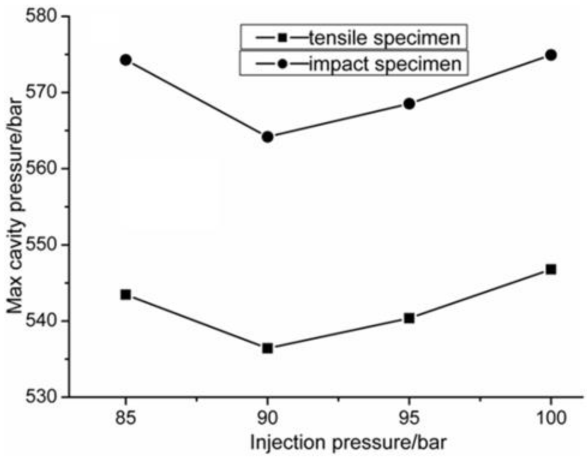


Fig. 8 Relationship between packing time and the maximum cavity pressure and temperature

Fig. 9 displays curve relationship between injection pressures and the maximum cavity pressure and temperature. The two curves are similar and with the increase of injection pressures, the two maximum cavity pressures firstly decrease and then increase constantly. When the injection pressures increase, although the maximum cavity temperature of tensile and impact samples fluctuates, the changes are small, being within 1°C. Therefore, injection pressures slightly affect the maximum cavity temperature of multiple samples.

Through above analysis, it can be seen that in the same injection process, the maximum cavity pressure of impact samples is larger than that of tensile samples. This is because the two samples have different lengths and it needs a shorter time for impact samples to fill cavities. After filling, tensile samples do not completely fill the cavities. Furthermore, over packing pressures appear due to excessive melts entering into impact samples. Therefore, compared with tensile samples, impact samples have larger maximum cavity pressure. The maximum cavity temperature of impact samples is larger than that of tensile samples because of different lengths. When impact samples fill cavities, tensile samples do not finish the filling. Meanwhile, too many melts enter into impact samples so little temperature is lost. Therefore, impact samples have higher maximum cavity temperature.



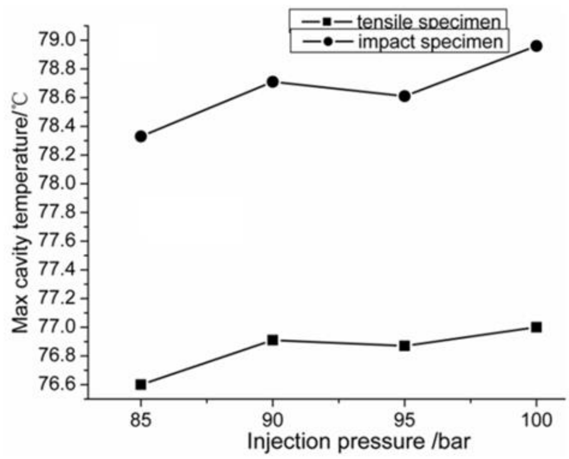


Fig. 9 Relationship between injection pressure and the maximum cavity pressure and temperature

5. Conclusions

An experimental work is carried out to study the effect of the injection molding parameters on the cavity pressure and temperature. The results indicate that the characteristics of curve of cavity pressures at different mold parts can be directly revealed and the differences of cavity pressure curve in symmetrical parts are accurately reflected by employing cavity pressure sensors. Furthermore, it reflects different changes of plastic melts in cavities. For tensile and impact samples, the influences of injection processing parameters on the maximum cavity pressures are in a decreasing order as packing pressure, melt temperature, mold temperature, packing time, and injection pressure. Packing pressure most significantly affects the maximum cavity pressure. For tensile and impact samples, the influences of processing parameters on the maximum cavity temperature are listed in a descending order as mold temperature, melt temperature, packing time, packing pressure, and injection pressure. Therefore, mold temperature has the most significant influences on the maximum cavity temperature. The results obtained illustrate well the evolution of the cavity pressure and temperature inside the mold cavity for different process parameters of the injection molding.

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EFFECT OF MICRO INJECTION MOLDING PARAMETERS ON CACITY PRESSURE AND TEMPERATURE ASSISTED BY TAGUCHI METHOD

Summary

The injection molding process is one of the most efficient processes where mass production through automation is feasible and products with complex geometry at low cost are easily attained. In this study, an experimental work is performed on the effect of injection molding parameters on the polymer pressure and temperature inside the mold cavity. Different process parameters of the injection molding are considered during the experimental work including packing pressure, packing time, injection pressure, mold temperature, and melt temperature. The cavity pressure is measured with time by using Kistler pressure sensor at different injection molding cycles. The results show the packing pressure is significant factor of affecting the maximum of diverse spline cavity pressure. The mold temperature is significant factor of affecting the maximum cavity temperature. The results obtained specify well the developing of the cavity pressure and temperature inside the mold cavity during the injection molding cycles.

Keywords: micro-injection molding, cavity pressure, cavity temperature, process parameters, Taguchi design.

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